

AIRCRAFT SURVIVABILITY

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Live Fire Test and Evaluation



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Mr. Mark Stewart is a Principal Systems Engineer at Lockheed Martin in Fort Worth, TX, where he is the F-35 Technical Lead for Vulnerability Analysis and Live Fire Test. Mark graduated from the University of Florida in 1983 with a BS in Mechanical Engineering and went to work at General Dynamics after graduation.



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JAS Program Office

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by Joseph Manchor

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by Hardy Tyson

It is difficult to separate vulnerability reduction from live fire test and evaluation (LFT&E), even though public law only requires a program to test, evaluate, and report. In part, this difficulty arises because the law requires that LFT&E "shall be carried out sufficiently early in the development phase...to allow any design deficiency demonstrated by the testing to be corrected in the design of the system...before proceeding beyond low-rate initial production." The observations in this article are drawn from the author's participation in a number of aircraft acquisition programs that included LFT&E.

28 F-35: First-Ever Fixed Wing Full-Up System Level

by Jeff Johnson and Timothy Staley

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News Notes

■ by Dennis Lindell

NDIA Vulnerability Reduction Workshop

On 17 May 2007, the Combat Survivability Division (CSD) of the National Defense Industrial Association (NDIA) conducted a workshop on aircraft vulnerability reduction, which was hosted by the Institute for Defense Analyses (IDA) and sponsored by the Deputy Director, Operational Test and Evaluation/Live Fire Test and Evaluation (DDOT&E/LFT&E). The objectives of this workshop were to understand the current environment for applying vulnerability-reduction technologies to existing and future aircraft and to identify steps necessary to improve vulnerability reduction in the future. The workshop was designed around three

aircraft types, under the assumption that the case for low vulnerability (LV) technology would be different in each of the three types. "Case study" briefings were given for each aircraft type: Joint Strike Fighter, representing fixed-wing tactical air; the multi-mission maritime aircraft (MMA), representing large fixed-wing aircraft; and the V-22 and AH-1 programs, representing helicopters. There were three workshop breakout sessions, and each focused on one of the aircraft types.

The table below shows some initial results of the workshop. The results focus on the five questions that were asked of the breakout session attendees: Is there a vulnerability-reduction problem? Is

LV treated less appropriately than other warfighter metrics? What programs would best be approached for low-vulnerability design? What should be done about vulnerability reduction? What other metrics would best feature low vulnerability in the requirements, design, and testing process? A final report from the workshop, due out in late summer 2007, will include actions identified from the workshop and specific recommendations for the NDIA CSD to pursue.

The Fifth Triennial International Aircraft Fire and Cabin Safety Research Conference

This conference takes place at the Tropicana Casino and Resort in Atlantic City, NJ, from 29 October through 1 November 2007. It is the fifth in a series of triennial conferences sponsored by international aviation authorities. These conferences were established to inform the international aviation community about recent, ongoing, and planned research activities in transport category airplane fire and cabin safety. The conference addresses both certification and operational issues.

Question	Helicopters	TACAIR	Large Aircraft
1. Is there a problem?	Yes	Yes: Need LV use cases in requirements development; some LV technologies need maturation (limited R&D funds)	Yes: Fire is an issue
2. Is LV treated differently?	Yes & No	Yes & No: it's the last link in the threat kill chain, but we haven't made the case for LV	Yes & No: LV is an afterthought in the design process
3. What programs should best be approached?	CH-53K, CSAR, AH-64, CH-46	Aircraft for which a credible LV use case can be developed; A/C currently using older technology	Not commercial aircraft; ask the warfighter
4. What should be done?	Link LV to force protection KPP; educate warfighter and acquisition personnel; link to safety	Develop LV use cases; develop vulnerability specifications; develop new metrics and M&S; educate warfighter and acquisition personnel	Link to safety; educate warfighter and acquisition personnel; link to force protection KPP; better metrics and M&S
5. Ideas for new metrics?	Force sustainability, recoverability; personnel casualties	Personnel casualties; longer kill levels; ties to safety metrics	Ties to safety metrics; ties to personnel survivability; ties to campaign level metrics

Table 1. Initial workshop breakout session results.



Research is being conducted to develop a totally fire resistant passenger aircraft cabin.

Research topics covered in the fire sessions include materials fire safety, fire resistant materials, cabin and hidden area protection, burnthrough, engine fire protection, and aircraft cargo compartments. Research topics that will be covered in the other sessions include crashworthiness, evacuation, and operational issues.

Complete conference details are available at <http://www.fire.tc.faa.gov> under the "Conference" tab at the top of the home page.

Larry Eusanio Receives Art Stein LFT&E Award



Mr. Larry Eusanio received the Art Stein Live Fire Test and Evaluation (LFT&E) Award on 26 June 2007 at the National Defense Industrial Association (NDIA) LFT&E Conference held at Charleston Air Force Base, SC. Mr. Eusanio's contributions to aircraft survivability began decades before the formal requirement for LFT&E. He spent 33 years at Cornell Aeronautical Laboratory (later called Calspan) in Buffalo, NY, where he worked on a variety of survivability and effectiveness programs. One of his first innovations was the development of a digital simulation in 1961 to conduct end game studies of the Eagle missile warhead-fuze combination to speed design tradeoff studies. This innovation was one of the first digital end game models. Before that time, end game studies were done manually using physical scale models to work out the geometry.

In another early study (1964), Mr. Eusanio led a project to determine the effectiveness of conventional munitions in realistic environments, such as vegetation and snow. Until then, effectiveness estimates were based on a bald earth. The Joint Technical Coordinating Group on Munitions Effectiveness (JTCG/ME) later used these models and data to produce the Joint Munitions Effectiveness Manuals (JMEM) for this type of weapon system, which were urgently needed for the Southeast Asia conflict.

In the 1970s and 1980s, Mr. Eusanio's primary emphasis was on the effectiveness of countermeasures as a function of various flight profiles. His tradeoff analyses led to identification of optimal countermeasure suites, tactics, and flight profiles for Army and Air Force standoff aircraft, such as Guardrail, Quick Fix, and Joint Stars. The Joint Stars project manager unofficially gave Mr. Eusanio credit for saving the program from early cancellation caused by Office of the Secretary of Defense (OSD) concerns about platform survivability.

In 1989, Mr. Eusanio moved to the Institute for Defense Analyses (IDA). It is fitting that he was hired, in part, based on a strong recommendation from Mr. Arthur Stein, an early pioneer of the aircraft survivability discipline. Until recently, Mr. Eusanio led the Air Systems LFT&E project for manned aircraft, anti-air weapons, missile defense systems, Joint Live Fire (JLF) of aircraft, and the Joint Aircraft Survivability Program (JASP). He continues his support of those programs today.

In 1991, Mr. Eusanio co-authored a briefing to the National Research Council's Committee on Weapons Effects and Airborne Systems. This briefing concerned the applicability of aircraft survivability test and evaluation methodologies for the LFT&E of aircraft such as the C-17 and F-22.

Mr. Eusanio has provided analytical support for most of the aircraft and anti-aircraft programs conducted to date under LFT&E statutory requirements. He and his IDA team have provided the Director, Operational Test and Evaluation (DOT&E) with test and evaluation concepts, technical reviews of service test and evaluation strategies, and technical reviews of detailed test plans. They have monitored key test events and provided independent assessments of the completed LFT&E in support of DOT&E's reports to the congressional committees. A number of these test and evaluation programs have resulted in substantial improvements to system survivability through changes to aircraft design or operational employment.

Mr. Eusanio has led initiatives to improve the state of LFT&E, place greater emphasis on the evaluation of human casualties, integrate battle damage assessment and repair (BDAR) into LFT&E, and integrate LFT&E with related safety tests.

Mr. Eusanio's academic credentials include a BS in Mechanical Engineering (1956) and an MS in Mechanical Engineering (1961), both from the University of Buffalo, as well as graduate studies in Operations Research (1968–1972) from the State University of New York at Buffalo. He has authored, co-authored, or made major contributions to more than 70 publications in survivability and effectiveness.

In summary, Mr. Eusanio has provided sustained analytical contributions to improve the survivability and effectiveness of U.S. military aircraft and weapon systems. These contributions have received visibility at high levels, including OSD and Congress, and they have addressed all classes of manned aircraft, including most of the aircraft currently in the defense inventory or in the acquisition process. Congratulations Larry! ■



First National Live Fire Test and Evaluation (LFT&E) Conference in Over 5 Years:

Successful, Productive, and Vital

■ by James O'Bryon

It has been more than 5 years since the last National Live Fire Test and Evaluation (LFT&E) Conference was sponsored at the Naval Postgraduate School in Monterey, CA. As one would expect, much has changed since then. Not only has terrorism now taken center stage, but with it have come new threats, new tactics, new technologies, and new sources of damage.

The conference held at Charleston Air Force Base (AFB), SC, in the last week of June 2007 was packed with nearly 60 presentations covering a wide variety of topics of importance to the LFT&E community.

The conference drew a crowd of people from a widely diverse community. Besides a strong representation from the Army, Navy, Air Force, and Marine Corps, other government participants included the Office of the Secretary of Defense (OSD), Director, Operational Test and Evaluation (DOT&E), Department of Homeland Security (DHS), Government Accountability Office (GAO), National Aeronautics and Space Administration (NASA), Department of Energy (DOE), and Defense Threat Reduction Agency (DTRA). Mr. Douglas Bruder, Director, Counter Weapons of Mass Destruction (WMD) Technologies Directorate, DTRA, gave the keynote presentation. Nearly 70 government and non-governmental agencies were represented at the conference, including all military branches and numerous defense hardware contractors, defense study agencies, test ranges, and universities performing work for the Department of Defense (DoD) and DHS.

Mr. Richard Sayre, the newly minted Deputy Director, OT&E/Live Fire Testing, set the tone for the entire four

days of discussions. He reminded the attendees that there are really only two overarching objectives of LFT&E—

- **Survivability**—Ensuring soldiers, sailors, airmen, and Marines have the equipment that will save their lives
- **Lethality**—Ensuring these same people that they can project the necessary force to destroy or incapacitate the enemy.

He went on to screen a recent video clip from Iraq showing an infantry soldier being fired upon as he negotiated an urban target. It showed the soldier being hit by a threat bullet in the chest, being knocked to the ground by the force of the impact, and then getting back up and successfully engaging his attacker, thanks to the body armor he was wearing.

A quick survey of the conference audience indicated that although a significant number of conference participants had been working on LFT&E issues for a number of years, it was the first LFT&E conference for many, and many had been working on LFT&E issues for less than five years. It was encouraging to see new people embarking on this important work. However, the presence of these newcomers also made clear the importance of ensuring the LFT&E lessons learned to date are communicated clearly and promptly to those entering the LFT&E workforce.

In light of the newcomers, the Deputy Director, OT&E/LFT&E authorized each conference participant to receive a copy of the CD "LFT&E Lessons Learned from Live Fire Testing: Insights Into Designing, Testing, and Operating U.S. Air, Land, and Sea Combat Systems for Improved Survivability and Lethality." [1] This CD

presents nearly 800 pages of unclassified LFT&E lessons learned applied to land, sea, and air systems. The CD sorts the information into several categories, including design changes, crew casualty reduction, modeling and simulation adequacy, test planning, LFT&E funding and resources, battle damage, and repair.

Mr. Sayre emphasized the priorities of the Director, OT&E, Honorable Dr. Charles McQueary, including "providing timely performance information to the warfighters." Mr. Sayre also stressed the importance of "enhancing test realism in early testing, including developmental testing." Other areas of current activity in the LFT&E office include—

- Congressional inquiry and hearings on body armor
- Congressional inquiry on combat helmets
- Participation on joint improvised explosive device (IED) defeat/joint test board
- Uparmor initiatives on high mobility multipurpose wheeled vehicle (HMMWV), trucks, and LTAS
- Lethality assessment of the M855 5.56mm ball round in current operations
- Standardization of wound ballistics test and assessment methodologies.

An update was also presented on the additional congressional LFT&E oversight requirements placed on the Deputy Director OT&E/LFT&E in light of Operation Enduring Freedom and Operation Iraqi Freedom. The FY07

National Defense Authorization Act (NDAA), Subtitle D, Section 231 adds the following to Section 139 of the Act: *"OT&E and/or Survivability testing of Force Protection Equipment (including non-lethal weapons)."*

Furthermore, this FY07 NDAA modifies Title 10, Section 2399 of the Act to read, *"Operational use of a system (or use of procurement funds) prior to full-rate production decision review, the Director [DOT&E] will submit a report to Congress on test adequacy and effectiveness and suitability."*

This congressional language demonstrates Congress's awareness that some smaller systems and upgrades fall below the level of a major system; however, because these systems are vital to the current conflict, they still require some DOT&E oversight even though they might not follow the traditional Milestone ABC paths of major systems.

Early on in the conference, a survey of the conference participants revealed that nearly half of them did not know what the Survivability/Vulnerability Information Analysis Center (SURVIAC) is or how to access it to support their LFT&E activities. Hence, the tutorials presented on the first day were especially valuable to those unfamiliar with SURVIAC and the value it can bring in support of LFT&E. Four tutorials were presented addressing the SURVIAC, Weapons Systems Technology Information Analysis Center (WSTIAC), Automated Joint Threat Systems Handbook (AJTSH), and Joint Aircraft Survivability Program Office (JASPO) "Threat Effects Video."

Dr. Lowell Tonnessen and Dr. Lenny Truett, both of Institute for Defense Analyses (IDA), and Mr. Marty Lentz of Wright-Patterson Air Force Base (WPAFB) gave informative presentations on the history and practices of LFT&E.

The presentations also heavily emphasized casualty reduction, which is the statutory focus of LFT&E. Aircrew, land vehicle crews, and ship

crew casualties were each addressed. Several presentations provided combat feedback on LFT&E issues, including presentations from aeromedical evacuation crew (AEC), ARL, and SURVICE engineering.

The conference understandably had an unusually high emphasis on battle damage and repair. There was also a significant focus on the vulnerability of aircraft to surface-to-air threats (e.g., RPGs, man-portable air defense system [MANPADS], small arms fire), particularly helicopters and large commercial aircraft being modified for military use (e.g., tankers, patrol aircraft, cargo).

Interestingly, although the bulk of DoD aircraft procurement funds are being directed at purchasing fixed-wing fighters (F-22, F-35, F/A-18E/F, etc.), the focus of the conference was not on small fighter aircraft but rather on helicopters and large transport aircraft, reflecting the concerns of those in the combat theater.

A number of briefings were also given to describe new LFT&E facilities that have recently come online, including UNDEX upgrades, tactical telemetry improvements, China Lake's Missile Engagement Threat Simulator, directed-energy warfare (DEW) facilities, and improved metrology capabilities.



Larry Eusanio (left) is congratulated by Mr. Richard Sayre (right) during presentation of the Arthur Stein Award.

The highlight of the conference was the presentation of the Arthur Stein Award. This award is periodically presented for

outstanding achievement in support of LFT&E. Mr. Richard Sayre presented this year's award to Mr. Larry Eusanio of IDA for his outstanding analytical support of LFT&E. Mr. Eusanio's more than 50-year career of outstanding service, beginning at Cornell Aeronautical Laboratory in western New York and continuing at the IDA as a leader of the LFT&E aircraft group, along with his numerous technical articles and presentations made him the obvious choice for this year's award.

As a side note, although Mr. Art Stein passed away more than a decade ago, his wife Dr. Annette Stein remains very engaged in a number of community pursuits near her home in Buffalo, NY. When she was contacted about the possibility of Mr. Eusanio being named for the award, her response was, "I can't think of a person who is more deserving. My husband knew Larry very well and had great respect for him." We were sorry that her overseas travel prevented her from joining us in Charleston for this special presentation.

When given the choice of when to have the next National Defense Industrial Association (NDIA) LFT&E conference (either in 2, 3, 4, or 5 years), more than 70 percent of the conference attendees indicated that 2 years was as long as they wanted to wait. Because of this, NDIA is now working on finding the appropriate location, hosts, and sponsors for the conference. ■

Reference

1. CDs (FOUO) can be purchased on a need to know basis from SURVIAC.



An Historic Perspective on Live Fire Test and Evaluation (LFT&E)

■ by Dr. Lowell Tonnessen

Editor's Note

The following is a transcript of Dr. Tonnessen's presentation from the Live Fire Test and Evaluation (LFT&E) Conference in Charleston, SC, held on 25–28 June, 2007.

Live fire test and evaluation (LFT&E) has now been a statutorily required program for more than 20 years, and each year, fewer of us remember its historic origins. In preparation for this article, I asked a number of professionals to nominate some of the significant events or ideas that have shaped the history of LFT&E. I've selected 15 items that provide a balanced perspective on the scope of LFT&E, the institutions involved in test and evaluation, and the evolution of LFT&E in practice. I'll present them in their historic order.

Joint Live Fire (JLF) Test Charter (1984)

The JLF test program preceded the statutory requirement for LFT&E. It resulted from a perceived absence of data from full scale vulnerability and lethality testing. The Joint Logistics Commanders endorsed the proposed test in December 1983, and the JLF test charter was signed by the

Director, Defense Test and Evaluation in March 1984. It differed primarily from later LFT&E in that JLF was funded by the Office of the Secretary of Defense (OSD), rather than the program being tested. Also, JLF tested fielded systems, rather than systems undergoing acquisition. Like LFT&E, however, it emphasized the need for system evaluations that are based on realistic survivability and lethality testing. JLF continues as a strong test program that complements LFT&E. It is administered by OSD's Office of the Director, Operational Test and Evaluation (DOT&E).

The Army Conducts Live Fire Testing of the Bradley Fighting Vehicle (1984–1987)

The Bradley tests began as a JLF program, but Phase II was conducted as an Army live fire test, with oversight from OSD. This live fire test was conducted under substantial scrutiny of the Congress and national media. Together with later tests of the M1A1 Abrams tank, the Bradley live fire test established disciplined standards for realistic testing and developed many of the procedures that have become standard practice for subsequent armored vehicle vulnerability testing. (See Figure 1. and 2.)

Congress Passes a Statutory Requirement for LFT&E of Armored Vehicles (1985)

The first statutory requirement addressed only armored vehicles. During the controversy concerning testing of the Bradley, Congress passed a statutory requirement for LFT&E of armored vehicles (Section 2362 of Title 10, United

States Code [U.S.C.]). Among its features was a requirement for side-by-side testing of armored vehicles against the system it was intended to replace. This statute was rescinded in 1994.

Congress Passes a Statutory Requirement for Survivability and Lethality LFT&E (1986)

In 1986 (FY87), the requirement for live fire testing of armored vehicles was expanded to require survivability LFT&E of all major manned platforms (land, sea, and air) that provide some degree of protection to the user, and lethality LFT&E for munitions and missile programs. Section 2366, Title 10, U.S.C. is what is commonly known as the "LFT&E law."



Figure 2. An Abrams live fire test. Realistic testing provides a basis for understanding the effects of combat hits.



Figure 1. The Bradley was tested in a full-up configuration, with a standard load of fuel and munitions.

JLF Tests are Used to Support LFT&E of the F/A-18 (1991–2000)

Through the years, numerous JLF tests have supported the LFT&E of acquisition programs. A prime example is the JLF tests that were done on earlier models of the F/A-18 and whose results were then incorporated into the F/A-18E/F LFT&E program. *Aircraft Survivability* describes these tests in its summer 2004 issue.

The Army Research Laboratory (ARL) Develops the Operational Requirements-based Casualty Assessment (ORCA) Model to Assess Personnel Casualties (1992)

The LFT&E law requires that LFT&E give primary emphasis to user casualties. There have been several methods for estimating whether an impacted crew member can perform the necessary functions. An early incapacitation methodology to evaluate the effectiveness of fragmenting munitions against infantry personnel was developed by Sperazza and Kokinakis (c. 1965). The ComputerMan Model initially was developed in 1980 to overcome some of the limitations of the Sperazza-Kokinakis methodology and to provide new casualty assessment capabilities. It is based on an extensive empirical wound ballistics database and on interviews with pilots to determine whether they could perform the functions necessary for controlled flight with specified types of injuries. ComputerMan is implemented within MUVES-S2. The ORCA model, whose development began in 1992, incorporates ComputerMan but expands the modeling and simulation to address non-ballistic effects.

Survivability Testing of F-22 Wing Demonstrates Value of Early Live Fire Testing (1992)

Early in the program, the F-22 program conducted a preliminary hydrodynamic ram test series of a wing box to determine whether it could survive impact from threat munitions. The test results were sufficiently definitive that the wing design was changed. This was only possible because the test had been conducted early in the program. A later live fire test in 2001 confirmed the ballistic tolerance of the new wing design.

DDG 51 Establishes an Analytical Approach to Conduct LFT&E of Ships (1994)

The Navy nominated the DDG 51 Class for LFT&E in April 1987. The LFT&E strategy was gradually refined, and by 1994 that strategy included many of the features that would become standard

practice for ship LFT&E. These included a total ship survivability trial (TSST), which addressed recoverability and crew response to damages that might be suffered by a ship after impact by a threat weapon. The DDG 53 and its crew experienced the first TSST. The DDG 51 program also established an analytical approach called a Damage Scenario-Based Engineering Analysis (DSBEA) as standard practice for LFT&E. The DSBEA approach employs an in-depth analysis for a limited number of damage scenarios using all available analytical means, including both computer modeling and human engineering judgment. Typically, a DSBEA will address only 20–30 scenarios. This approach is in contrast to many vulnerability models that address hundreds or thousands of impact scenarios, but with significant limitations in scope or validity. The intent of a DSBEA analysis is to predict, through analysis and limited testing, the chain of events that might occur after an actual threat attack.

Congress Establishes DOT&E as the Oversight Authority for LFT&E (1994)

The 1994 Federal Acquisition Streamlining Act (FASA) transferred LFT&E responsibility to DOT&E. The original law had specified the Secretary of Defense as responsible for LFT&E, but did not establish a director of LFT&E or delegate responsibility to a particular office within OSD. Until

1994, LFT&E responsibility had been in various offices in the developmental side of OSD. At one time, responsibility for air and space programs was separated from land and maritime programs. The 1994 FASA act linked LFT&E and operational test and evaluation (OT&E) and laid the foundation for a unified assessment of effectiveness, suitability, and survivability. (See Figure 3.)

Dynamic Rotor Blade Testing Introduces a New Level of Realism to Helicopter Live Fire Testing (1998)

Until the landmark JLF tests in China Lake in 1998, rotor blade vulnerability had been limited to static loaded testing, sometimes with follow-on dynamic spin-up of the rotor blades to determine dynamic effects. China Lake developed the test technology to impact a moving rotor blade on a helicopter system. The JLF tests of AH-1 helicopters demonstrated cascading effects that would not have been observed in static testing, and thus brought increased test realism to the LFT&E of helicopter programs.

The Sense and Destroy Armor (SADARM) LFT&E Program Includes End-to-End Lethality Testing (1998)

No LFT&E program for a munition or missile has ever needed a waiver from full-up, system-level testing. In part, this is due to LFT&E programs that include end-to-end shots that are

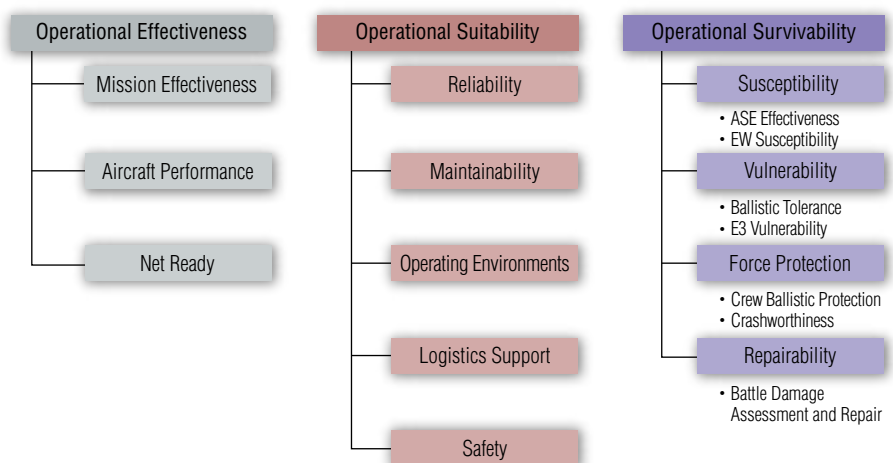


Figure 3. DOT&E provides an integrated assessment of operational effectiveness, suitability, and survivability.

useful to both operational and live fire test programs. This has been especially true for the so-called smart weapons that have relied increasingly on end-to-end test flights or firings of live-warhead munitions against a selection of realistic, representative targets. An early example was the Army's SADARM program, which included some realistic targets in selected DT firings and an entire threat firing battery in the IOT. Today, this trend continues in such programs as Joint Air-to-Surface Standoff Missile (JASSM), Small Diameter Bomb, Excalibur, and Guided Multiple Launch Rocket System (MLRS) Unitary, and should be considered the normal means to provide realistic lethality data.

The USS Cole is Attacked by Terrorists (12 October 2000)

The USS Cole was attacked by terrorists using a small boat loaded with explosives. Through the heroic actions of the crew, the USS Cole was saved, but the attack highlights the importance of asymmetric terrorist threats for U.S. ships, even for those operating in primarily permissive environments like Yemen. The implication for LFT&E is that asymmetric threats are expected threats and need to be addressed in survivability test and evaluation, whether or not they are included in formal threat documents. (See Figure 4.)

JLF Expands its Scope to Address Sea Systems (2001)

The original JLF charter did not include the testing of ships and submarines. In 2001, JLF first funded the testing of sea systems. In 2005, an advisory panel was created that greatly expanded the attention to sea system JLF. One of the tests funded by this program has been non-explosive testing that might (at some future time) be combined with modeling and simulation to replace the need for the large explosive charges currently used in full-ship shock testing.

Congress Establishes a Statutory Requirement for Force Protection and Survivability in an Asymmetric Threat Environment (2004)

The LFT&E law is a test and evaluation law. It requires realistic survivability and lethality testing, with primary emphasis on personnel casualties of U.S. forces. The National Defense Authorization Act (NDAA) for FY05 addresses personnel casualties from a complementary perspective. It requires that key performance parameters (KPP) for force protection and survivability be established for all manned systems that may be employed in an asymmetric threat environment. In his implementing memo, General Peter Pace distinguished the key terms as follows: "Force Protection attributes are those that contribute to protection of personnel. Survivability attributes are

those that contribute to the survivability of manned systems." Although the law does not directly require test and evaluation, KPPs are non-tradable requirements that necessitate test and evaluation.

Congress Requires DOT&E to Provide Section 231 Reports in Support of Rapid Fielding (2006)

LFT&E and OT&E normally are reported by DOT&E prior to a system's decision to proceed beyond low-rate initial production (BLRIP). In today's defense climate, however, systems sometimes are deployed to Iraq or Afghanistan before proceeding to full-rate production. The NDAA, Section 231 for FY07 modifies Title 10 to require that DOT&E report known capabilities and limitations to the Congress in these and similar circumstances. These reports, which are known informally as "Section 231 reports," enhance the relevance of OT&E and LFT&E in a rapid fielding environment.

Conclusion

These are a few highlights of LFT&E and significant related events in the past 20 years. They show that LFT&E continues to evolve to address the needs of decision makers regarding survivability and lethality, and to adapt through the years to a changing defense and political environment. They also show the complementary roles that JLF and LFT&E have played in assessing the survivability and lethality of new and fielded systems. Finally, as we review the history of LFT&E in the light of the current conflicts in Iraq and Afghanistan, we should recognize that LFT&E's emphasis on personnel survivability has become increasingly relevant.

Thank you all for being part of the history of live fire test and evaluation. ■



Figure 4. The USS Cole highlighted the importance of asymmetric threats for U.S. ships.



Joint Live Fire/Aircraft Systems Program

■ by John Murphy and Jon Wheeler

An analysis of historical and more recent combat events indicates that our U.S. military aircraft—both fixed and rotary wing—continue to be somewhat vulnerable to various enemy threats, including uniformed combatants, insurgents, and terrorists. Because of our nation's acquisition trend to purchase fewer but more expensive air assets, we must continue to reduce our aircraft vulnerability to enemy threats. Survivability is as much a necessity for our current air vehicle inventory as it is for our newest acquisitions.

The first step in addressing aircraft survivability is to assess when and by what threat(s) an aircraft is susceptible. Aircraft are more susceptible to hostile threats during takeoff and landing when they are relatively slow and low to the ground. Damage to C-130s during Operation Just Cause and in Kosovo came from small arms and automatic weapons fire, with most rounds striking the sides and lower half of the aircraft. Such damage can occur to any aircraft during takeoff and landing depending on perimeter security. Another threat during takeoff and landing is the man-portable air defense

system (MANPADS), as evidenced by the DHL airliner, C-5, and C-17 incidents in Baghdad. However, threats are present during each mission phase.

On 24 March 2003, during Operation Iraqi Freedom, 33 Apache rotorcraft flew ahead of the Army's Third Infantry Division to attack an Iraqi Republican Guard regiment in the suburbs of Karbala. Small arms fire and rocket-propelled grenades (RPG) hit 30 of these rotorcraft; enemy combatants shot down one Apache and took two crewmembers prisoner. Air-to-air and surface-to-air missiles present another concern. These missiles [radio frequency (RF) guided, infrared (IR) guided, and anti-radiation missiles (ARM)] can attack from short range, medium range, and long range. The results of these threats may include engine and fuel tank fire, internal explosion, structural airframe damage, or aircrew injury. Aircraft can sustain any level of kill—from immediate kill to inability to accomplish a mission because of damage inflicted on mission-critical equipment. Even aircraft as stealthy as the F-117 are susceptible, as evidenced by the downed F-117 over Kosovo on 27 March 1999.

The second step in addressing aircraft survivability is to understand how threats affect the aircraft when countermeasures fail and the aircraft is hit. Understanding the tools, methodologies, and test series used to assess aircraft susceptibility and vulnerability is important when evaluating the overall survivability of an aircraft. These tools and methodologies include—

- Target description(s)
- Flight path generation models
- Missile engagement (RF or EO/IR) models
- SA/AW and AAA engagements
- Missile end game

- Computation of vulnerable area and repair times
- Fire and explosion predictions
- Component damage and kill values.

For a specific aircraft, computer models are used to identify areas vulnerable to specified threats. Once vulnerable areas are identified, a level of confidence is associated with these values. Any values with a low to medium confidence level can be candidates for live fire tests. However, combat data or data from previously completed joint live fire (JLF) projects and live fire test and evaluation (LFT&E) programs can be used to help address the low to medium confidence levels.

The Office of the Secretary of Defense (OSD) initiated the JLF program in March 1984 to establish a formal process for testing and evaluating fielded U.S. systems against realistic threats. The program's primary objectives are to assess the vulnerability of our armored vehicles, ships, and military aircraft to likely threats and to evaluate the lethality of our munitions against realistic targets. The program continues today under the Deputy Director, Operational Test and Evaluation (DDOT&E)/LFT&E.

Current and future JLF/Air projects in FY07 will provide empirical and non-empirical data on fielded U.S. aircraft so the military can better understand their vulnerability and identify ways for reducing this vulnerability. These efforts will provide information to—

- Aid in combat mission planning
- Increase aircraft and aircrew combat survival and effectiveness
- Provide battle damage assessment repair training
- Provide design recommendations to reduce the ballistic vulnerability of current and future U.S. aircraft.



RPG threat

This valuable information is made available to the test and evaluation community, system program offices, and warfighters. The FY07 JLF/Air program consists of vulnerability tests and assessments on the following rotorcraft and fixed-wing aircraft:

- AH-64
- CH-47D
- CH-53E
- OH-58D
- UH-60
- Predator unmanned aerial vehicle (UAV)

Efforts for assessing large turbofan engine and control surface vulnerability to the MANPADS threat were initiated in FY04 and FY05, respectively. These efforts now continue in FY07. A tri-service effort to better understand rotorcraft vulnerability to RPGs was completed in FY05.

JLF/Air projects support the following focus areas—

Warfighter Needs

JLF/Air works with the Joint Combat Assessment Team (JCAT), user commands, and program offices to address warfighter needs in order to understand the types of combat damage experienced during operations in Iraq [Operation Iraqi Freedom (OIF)] and Afghanistan [Operation Enduring Freedom (OEF)], determine how serious the damages are, and identify any quick vulnerability-reduction fixes. If no quick fixes exist, the solution may be to alter tactics, techniques, and procedures to limit exposure time to

the threat(s). Below are descriptions of projects with current funding.

■ **OH-58D Kiowa Warrior**—In FY05, three OH-58D Kiowa Warrior efforts were funded under JLF/Air to address damage incurred in OIF and OEF. These efforts continue in FY07: Cockpit—Aircrew Ballistic Vulnerability, Fuel Subsystem Ballistic Vulnerability, and Rotor Control Subsystem Ballistic Vulnerability.

- **Cockpit**—Aircrew Ballistic Vulnerability. JLF/Air planned and conducted gunfire tests on components of the OH-58D cockpit to understand the potential for system kills and aircrew injury. Testing was completed during the first quarter of FY07; the final report should be available in the fourth quarter of FY07.
- **Fuel Subsystem Ballistic Vulnerability**—JLF/Air planned and conducted gunfire tests on components of the OH-58D fuel supply subsystem to understand the potential for subsystem-system disablement and fuel ignition. Testing was completed during the first quarter of FY07; the final report should be available in the fourth quarter of FY07.
- **Rotor Control Subsystem Ballistic Vulnerability**—Program personnel planned and conducted gunfire tests on components of the OH-58D main and tail rotor control subsystem (mechanical and

hydraulic) to understand the potential for subsystem degradation/disablement and system kills. Testing was completed during the first quarter of FY07; the final report should be available in the fourth quarter of FY07.

Legacy System Product Improvement

JLF/Air works with the program offices to address legacy aircraft issues (for example, identifying and quantifying legacy system vulnerabilities and verifying legacy survivability enhancements).

- **A-10 Warthog**—In FY05, JLF/Air funded an A-10 Warthog Dry Bay Foam Verification effort. These efforts will be published in a report in FY07.
- **Dry Bay Foam Verification**—JLF/Air tested and validated a previous dry bay foam formulation used in the A-10 fuselage area using a combination of airflow and ballistic testing. However, the formulation for the A-10 wing and fuselage dry bay foam has changed. This formulation had been subjected to ballistic testing with airflow. The A-10 SPO was concerned about dry bay fire vulnerability. Any potential vulnerability to fire in this unproven dry bay foam needed to be identified because the A-10's life was extended to the year 2028. Testing has been completed. The revised dry bay foam formulation passed the airflow test.
- **CH-53E Super Stallion**—The CH-53E project contributes to PMA-261 efforts to reduce the vulnerability of the fielded CH-53E and identifies areas to upgrade the heavy lift replacement (HLR). In FY06, JLF/Air conducted testing on the CH53E fuel system to demonstrate new fuel vulnerability-reduction technologies. In FY07, JLF/Air will conduct CH-53E ballistic testing of the flight controls and tail rotor systems.



MANPADS launch

- **UH-60 Black Hawk**—JLF/Air explored dry bay foam vulnerability-reduction alternatives, improved durability gearbox (IDGB) run-dry ballistic vulnerability tests, and tested UH-60 engine nacelle fire extinguishing system effectiveness against ballistic threats. The results of these projects are applicable to all tri-service H-60 aircraft and to future production variants, including the Army's UH-60M and the Navy's MH-60R and MH-60S.



UH-60 Black Hawk

- **Dry Bay Foam Vulnerability-Reduction Alternatives**—The FY04 effort involved detailed test planning and hardware acquisition. Preliminary research on existing information (data search) began in March 2004. The FY05 effort was for material acquisition, testing, and the final report. Testing was completed during the first quarter of FY06; the final report should be available in the fourth quarter of FY07.
- **IDGB Run-Dry Ballistic Vulnerability Tests**—The FY04 effort involved detailed test planning and hardware acquisition. The FY05 effort was for material acquisition, testing, and the final report. Testing was completed during the second quarter of FY06; the final report should be available in the fourth quarter of FY07.

Vulnerability-Reduction Testing/Technology Insertion

JLF/Air works with the Joint Aircraft Survivability Program (JASP) Vulnerability Reduction Subgroup and program offices to test vulnerability-reduction technologies developed by JASP.

Enhanced Powder Panel

Validation—JLF/Air worked to validate the design and effectiveness of the enhanced powder panel. This is the final step in taking the proven technology from the laboratory and subscale demonstrations to full-scale testing and, finally, to the field. Commercial powder panels are not always effective as a passive fire extinguishing device; few alternatives exist to active fire suppression for aircraft dry bays. Previous testing shows that commercial powder panels have a limited effectiveness range, detracting from their usability in various applications. Enhanced powder panels offer potential improvement for passive fire extinguishing, providing a reliable and virtually maintenance-free means of fire mitigation for aircraft dry bays.

Baseline testing of these panels showed increased powder release, better powder dispersion for longer periods, and greater design flexibility. Subscale fire testing at China Lake (NAWCWD) in 2003 demonstrated feasibility and effectiveness improvement over commercial powder panels. The FY04 Joint Aircraft Survivability Program Office (JASPO) Vulnerability Subgroup project, EPP Development, will conclude with a production-ready EPP design demonstrated in smaller scale testing. However, testing on full-scale aircraft is required to validate the production-ready EPPs and to demonstrate their field readiness. Testing will begin in the fourth quarter of FY05; the final report should be available by the fourth quarter of FY05.

- **Predator**—Following the DDOT&E/LFT&E's desire for closer integration of the JLF/Air program with other DOT&E investment programs, program personnel will base shotlines for this effort on the Computation of Vulnerable Area Tool (COVART) analysis previously completed under the JASP's Predator Vulnerability Analysis (FY03). In Phase I (FY06), JLF/Air conducted component-level vulnerability testing of two different UAV engine types. During Phase II (also in FY06), JLF/Air conducted component-level vulnerability testing of the fuselage and wing fuel tanks of the Predator B.



Predator

JLF/Air supports the UAV Program Office in reducing aircraft vulnerability to present and future blocks of the aircraft. Although UAVs are unmanned and thus exempt from Title 10 LFT&E, UAVs—and therefore their survivability—are increasingly critical to battlefield situational awareness and mission success. Our UAV analysis identified potential vulnerabilities in the Predator design that future Predator versions can address. Lessons learned from this effort can be applied to other UAVs/UCAVs as well. Testing started in the second quarter of FY07; the final report should be available by the first quarter of FY08.

Emerging Threats of Interest

JLF/Air works with intelligence agencies, user commands, and program offices to address emerging threats of interest.

- **RPG**—Recent conflicts show that our front-line rotorcraft systems are vulnerable to attack from RPGs. The JLF/Air FY04 program investigated the vulnerability of front-line rotorcraft to this threat by testing AH-1S Cobra aircraft. The goal of this effort is to understand the damage mechanisms of this threat and to identify potential survivability enhancements for rotorcraft. This multi-year tri-service program led to Phase IV, which was completed in the first quarter of FY07. Survivability/Vulnerability Information Analysis Center (SURVIAC) personnel are authoring a combined final report that should be available by the fourth quarter of FY07.
- **MANPADS**—JLF/Air initiated a three-phase effort to investigate the vulnerability of large turbofan engines to MANPADS. This effort will address the following long-standing issues:
 - What is the inherent vulnerability of an operating engine when hit by a MANPADS?
 - How does the damage state compare to pretest predictions?
 - How does the damage affect engine operation and thrust?
 - How will the thrust alteration affect safety of flight?
 - What is the kill mechanism (if damage produces a kill)?

JLF/Air personnel successfully completed Phase I testing on a non-operating TF-39 engine earlier this year and produced a Quick Look Report. Tests included live and inert missiles to assess the engine's damage response and to perform a quick-look assessment of damage predictions. This project marked the first time live MANPADS were launched from a gun barrel to precisely control the shotline, impact velocity, hit point, and detonation delay, thus reducing test risk and allowing

direct correspondence with modeled conditions. Testing will continue with a CF6 engine common to the C-5, E-4, and large commercial aircraft. Results from this effort will support large aircraft operational risk assessments and vulnerability analyses, leading to improved warfighter protection.

- **AH-64 Fire Extinguishing Technology Evaluation**—In FY06, JLF/Air began assessing the effectiveness of Solid Propellant Gas Generators (SPGG) in extinguishing fires. With Halon 1301 being phased out, aircraft platforms need new and better ways to extinguish fires, particularly in engine nacelles. The Army Apache Equipment Program Manager endorsed this project as a technology demonstration for the helicopter. These tests use commercial off-the-shelf (COTS) SPGGs with an active agent embedded in the unit. Testers are using an Apache helicopter engine nacelle simulator for repetitive fire tests with realistic airflow passing through the simulator.

After a stable fire is produced in the simulator, the SPGG units are ignited to extinguish the fire. For each test, testers change

the location of the fire and the SPGG unit before ignition. To reach validation status, the program requires five consecutive extinguished fires in the simulator. Data generated from this test will indicate whether the technology can be pursued further in a certification environment as a replacement for the HFC-125 now in use. Test planning occurred in FY06 and FY07. Test execution will occur in FY07 with analysis performed in FY07 and FY08.

- **F-35 API Functioning**—JLF/Air conducted a COVART-based vulnerability assessment to coincide with the development and acquisition of the F-35 weapon system and to verify the survivability of the weapon system to various threats. Part of this assessment is examining fires started by armor-piercing incendiary (API) projectiles igniting in the aircraft dry bay areas. The functioning characteristics of API projectiles against and within the new advanced composite materials used in the new aircraft are unknown. This effort will produce a consistent and accurate method for quantifying the light intensity and duration of ballistic impacts against graphite epoxy test panels similar to those used on the



AH-64



Live Fire Test

F-35. Testing was completed in the first quarter of FY07. Analysis will be complete and a report available in the fourth quarter of FY07.

- Foreign Unguided Rocket Lethality**— This JLF/Air program will provide basic warhead characterization data and lethality estimates (against helicopters) for a single, foreign, unguided rocket warhead. Results will be used for aircrew training, threat identification, tactics refinement, aircraft vulnerability reduction, and battle damage assessment and repair (BDAR). The derived data will also be used to better understand the vulnerabilities of deployed aircraft to unguided rockets. Testing was completed in the fourth quarter of FY06; analysis will be completed and a report available in the third quarter of FY07.
- Fragment Restraint Solution for HH-60 A/L**—JLF/Air began testing a hardware solution to reduce system-level ballistic vulnerability of the onboard oxygen-generating system (OBOGS) for the HH-60 A/L Black Hawk medical evacuation (MEDEVAC) airframe. The solution is not intended to stop the possible projectile but to contain any resulting fragments in the aircraft's confined space. Testing was completed in the

third quarter of FY07; analysis will be completed and a report available in the first quarter of FY08.

- Internal Flare Bucket**

Mitigation— JLF/Air is initiating live fire testing to investigate the response of internally mounted flares to projectile impact. The initial effort is to gather dimensional data for the internal flare bucket and to design the interface portion of a heavy weight dry bay simulator to acquire temperature, pressure, and mechanical property data for developing the mitigation design criteria. Testing began in the third quarter of FY07; analysis will be completed and a report available in the first quarter of FY08.

The U.S. military is purchasing fewer but more expensive weapon systems and is extending the life of fielded weapons systems beyond their intended life spans. Aircraft survivability is now a "critical system characteristic" and is a distinct and important design discipline. Top-level survivability design guidance is prescribed; quantified requirements on the susceptibility and vulnerability of aircraft are now routinely specified. Methodologies exist for assessing aircraft susceptibility and vulnerability. Survivability testing has been mandated at some level for decades. Given today's multi-faceted global threat environment and the continuously evolving cat-and-mouse game of threat versus countermeasure, the first step in addressing aircraft survivability is understanding how these threats affect the aircraft when countermeasures fail and the aircraft is hit. The JLF/Air program continues to provide a valuable avenue for testing the vulnerabilities and vulnerability-reduction equipment developed for fielded U.S. aircraft. ■



H-1 Upgrades Helicopter Live Fire Test and Evaluation (LFT&E) Program

■ by Michael Kouvarakos and Darrell Liardon

The United States Marine Corps (USMC) H-1 Upgrades program will replace the existing fleet of Bell Helicopter AH-1W Super Cobra attack helicopters and UH-1N Huey utility helicopters with improved AH-1Z attack helicopters and UH-1Y utility helicopters. The current program calls for buying 180 AH-1Z and 100 UH-1Y aircraft. All AH-1Z helicopters will be remanufactured from existing AH-1W aircraft. Ten UH-1Y helicopters will be remanufactured, but the rest will be brand new aircraft. The USMC will have airframes with 10,000-hour service life, new and completely integrated glass cockpits, a highly maneuverable and reliable four-bladed rotor system with composite blades, and an upgraded drive train, all common to both aircraft. In fact, a major benefit of the program is that it maximizes commonality of the AH-1Z and UH-1Y (approximately 84 percent of the major components are common), which will reduce the logistics footprint and operations and support costs. The AH-1Z will have two new weapons pylons, which accommodate internal fuel and additional weapons stations for increased lethality. The UH-1Y will have its forward fuselage section extended by 21 inches to accommodate additional space for avionics equipment. The UH-1Y will

also receive upgraded General Electric T-700-GE-401C engines. Overall, both aircraft will have increased capability and performance over the existing platforms, including range; payload; speed; and high-altitude, hot-day performance. Figure 1 shows the AH-1Z and UH-1Y.

Survivability Design Features

Survivability has been important in the design of the H-1 Upgrades since program inception. Building on the commonality of the two aircraft, all survivability features are common. In fact, the survivability features are identical with the exception of the fuel system installations and portions of the crew armor. Attention has been given to both vulnerability- and susceptibility-reduction features. Vulnerability-reduction features include ballistically tolerant components, redundant structure and systems, crew station armor, and fire and explosion protection capability. Use of integrated aircraft survivability equipment, such as missile, laser, and radar warning receivers; a countermeasures dispensing system; and an engine infrared suppressor that is turned outward to reduce exhaust plume impingement of the tailboom reduces aircraft susceptibility to missiles.

Survivability design improvements over legacy aircraft include an increased ballistically tolerant main and tail rotor system, increased ballistically tolerant large diameter control tubes, an ullage nitrogen inerting system, hydraulic reservoir level-sensing with isolation valves, two additional countermeasures dispensers, and energy-attenuating armored crew seats. Foam and backing board are installed at the top surface of the fuel cells inside the weapons pylon assembly of the AH-1Z to minimize fuel spray from an exiting projectile, which could be ingested by the engine. The UH-1Y has a ballistically tolerant tail rotor drive system, run dry gearboxes, a dry bay fire suppression system, a suction fuel transfer, energy attenuating troop seats, and an engine infrared suppressor system.

Program Scope

The upgraded AH-1Z and UH-1Y are considered “covered” systems under United States Code (U.S.C.) Title 10 2366. Thus, they are subject to the live fire test (LFT) law, which requires realistic survivability testing of fully operational, combat configured systems. Therefore, the AH-1Z variant was required to undergo full-up system-level (FUSL) testing. However, because it was considered unreasonably expensive and impractical for the UH-1Y to also undergo FUSL, especially because there was substantial commonality between the two aircraft, the Office of the Secretary of Defense (OSD) granted a waiver from FUSL. An alternative LFT plan was developed that included using a UH-1Y static test article (STA) in a nearly full-up system-level (NFUSL) configuration, which focused on testing unique to the UH-1Y. Overall, the H-1 Upgrades LFT program used a building block approach that commenced



Figure 1. USMC AH-1Z (left) and UH-1Y (right).

at the component level, progressed to the subsystem level and full-scale STAs, and finally culminated with the full-up test. Notably, the H-1 Upgrades program is the first Department of Defense (DoD) program to execute an extensive live fire test and evaluation (LFT&E) program that included FUSL of a flight test article configured for combat before full-rate production.

The DoD-approved Test and Evaluation MasterPlan (TEMP) outlined the roadmap for the H-1 Upgrades LFT program. It contained specific vulnerability issues that needed to be addressed through testing or analysis. These issues were separated into three categories: AH-1Z and UH-1Y common vulnerability issues, AH-1Z-unique vulnerability issues, and UH-1Y-unique vulnerability issues.

- Common vulnerability issues included main and tail rotor drive, main rotor hub, main and tail rotor blade, transmission, gearboxes, tailboom, and fuel system.
- AH-1Z-unique vulnerability issues included airframe structure, fire and hydraulic ram to the weapons pylon fuel tank, engine fuel ingestion from the weapons pylon fuel tank, and protection of the crew.
- UH-1Y-unique vulnerability issues included airframe structure and protection of the crew and troops.

Discussion of Test Series

A total of 21 ballistic tests, focusing on critical areas of the aircraft, were conducted from 1997 to 2006. Most of the tests were conducted at the Weapons Survivability Laboratory located at Naval Air Warfare Center Weapons Division, China Lake, CA. However, several other ballistic tests, including all of the post-damage fatigue tests, were conducted at Bell Helicopter in Fort Worth, TX. Table 1 summarizes each individual test series. The following bullets provide a brief explanation of the areas tested.

Drive Systems

The H-1 Upgrades LFT program used a 214ST helicopter (see Figure 2) provided by Bell Helicopter as a test fixture for several of the drive system component-level ballistic tests early on in the test program. The 214ST facilitated high-fidelity testing under realistic conditions and also offered the opportunity for the evaluation of cascading failure modes that would not otherwise be present if a spin fixture was used. The 214ST was modified, in most cases, to replicate the H-1 Upgrades test component. The tail rotor, intermediate, and combining gearboxes were tested to determine continued functionality of the gears and bearings following ballistic impact and continued operation during a loss of lubrication situation. Other areas of the drive system, such as the main driveshaft and tail rotor driveshaft, were also tested. Two types of shotlines were achieved on each driveshaft: a single aperture (tangential penetration



Figure 2. Bell 214ST helicopter.

of the cylinder) and a double aperture (diametric penetration of the cylinder) wound. Finally, the main rotor gearbox was tested in a dynamic test fixture different from the 214ST in order to investigate ballistic tolerance of its gears and bearings.

Test Title	Date Completed	Number of Shots
AH-1Z Dry Bay Fire Protection	January 1998	114
Tail Rotor Drive Shaft, Hangar Bearing, and Support Assembly	March 1998	11
Combining Gearbox	September 1998	3
UH-1Y Dry Bay Fire Protection	June 1999	21
Main Input Driveshaft	January 2000	4
42° Gearbox	October 2000	4
Main Rotor Actuator	April 2001	4
90° Gearbox	May 2001	4
Main Rotor Pitch Link	July 2001	6
Tail Rotor Blade	June 2002	4
Main Rotor Cuff	August 2002	4
Main Rotor Blade	October 2002	4
Main Rotor Yoke	April 2003	5
Main Rotor Pitch Change Adapter	April 2003	4
Swashplate Assembly	June 2003	11
Main Rotor Gearbox	January 2004	10
AH-1Z Wing Hydraulic Ram/Fuel Ingestion	November 2005	5
Wing Mounted Munitions	April 2005	7
AH-1Z STA	October 2005	24
UH-1Y STA/NFUSL	March 2006	27
AH-1Z FUSL	May 2006	19

Table 1. Summary of H-1 upgrades live fire tests.



Figure 3. Dynamic main rotor blade test during the AH-1Z FUSL test series.

Rotor Blades and Hub

A key feature in the H-1 Upgrades program is the design of a bearingless rotor system that uses composite main and tail rotor blades and hubs. This rotor system offers significantly improved reliability because it has fewer parts, while system design and advanced composite material construction have improved the ballistic survivability. The following components were tested under static load at critical locations of high stress to verify ballistic integrity: main rotor blade, main rotor cuff, main rotor yoke, main rotor pitch change adapter, and tail rotor blade. Following ballistic testing, each specimen underwent post-damage fatigue testing. Fatigue testing was conducted under simulated operational flight load conditions to reflect controlled flight and landing. The ballistic impact performed on the main rotor blade specimen under static load was repeated on a rotating blade during the AH-1Z FUSL test series (see Figure 3) to compare the degree of damage between the static and dynamic tests while using the same threat. Figure 4 shows post-damage impact photos for both the static and the dynamic conditions.

Fuel Tanks and Dry Bay Fire Protection System

Both the AH-1Z and UH-1Y STAs were used to investigate the efficacy of the dry bay fire protection system. Each STA was outfitted with fuel cells that were surrounded by either a combination of foam with a composite backing board or fire extinguishing powder-filled panels. Combinations of dry-to-wet (impact the dry bay first) or

wet-to-dry (impact the fuel cell first) shotlines were executed to challenge the fire protection system and prevent a sustained fire. Consequently, the performance of each fuel cell's self-sealing material was evaluated based on the extent of leakage into adjacent dry bays and into the troop compartment of the UH-1Y.

Weapons Pylon Assembly

Each weapons pylon assembly on the AH-1Z was redesigned to accommodate an internal fuel tank for increased fuel capacity and an additional weapons station for increased lethality. As a result of the new weapons pylon, it was necessary to investigate the potential vulnerabilities associated with the presence of the internal fuel tank. The test setup included a fabricated engine inlet, an operating engine, and the weapons pylon under a static load simulating a forward-flight maneuver. Different shotlines were examined to determine whether fuel spray caused by an exiting projectile could be ingested by the engine (see Figure 5) and to

determine the level of damage to the weapons pylon from hydraulic ram effects. In addition, ballistic impact was conducted to determine whether the combination of foam and backing board can prevent a sustained fire in the leading and trailing edge dry bays of the weapons pylon. Following the aforementioned test series, the weapons pylon assembly was mounted onto an AH-1S aircraft and loaded with 2.75-inch rockets, a Sidewinder missile, and a Hellfire missile. The purpose of the test was to evaluate the response of the warhead and rocket motor of all three munitions to ballistic and fragment impacts, as well as the likelihood of fire, explosion, and structural damage.

Airframe and Tailboom Structure

Both the AH-1Z and UH-1Y STAs were statically loaded in test fixtures used previously for static and low- and high-cycle structural fatigue testing. The purpose of this test was to determine the ballistic tolerance of the fuselage and tailboom structure, as well as to examine the vulnerability of the



Figure 4. Static (left) versus dynamic (right) main rotor blade damage.



Figure 5. Engine fuel ingestion test.

fuselage fuel tanks to ballistically induced hydraulic ram effects. Impact locations were chosen at regions with high stress or high loads. The AH-1Z STA included the fuselage, the tailboom, a simulated main rotor gearbox, and a left- and right-hand simulated weapons pylons assembly. Areas of ballistic interest consisted of a major fuselage splice joint, an attachment area for the tailboom to the fuselage, a tail rotor gearbox support structure, and main rotor gearbox pillow block mounts. For the UH-1Y, the following critical areas of the fuselage underwent ballistic testing: left-hand transmission lift beam, right-hand transmission lift beam attachment point, and both left- and right-hand tailboom attachment point support beams. Both STAs had fuel cells installed so the tests could investigate hydraulic ram damage to the surrounding structure—particularly the composite conformal skin panels and composite floor panels underneath the fuel cells.

Crew Vulnerability

One of the design criteria for the H-1 Upgrades aircraft is enhanced crew protection. Both the AH-1Z and UH-1Y crew compartments utilize energy-attenuating armored seats and side armor panels to provide protection for the pilot and co-pilot. The aircraft system survivability specification has a requirement for a crew protection level. Therefore, an assessment was conducted for both platforms from a variety of shotlines around the aircraft. In addition, the countermeasures

dispenser of each platform was investigated to determine potential vulnerability to the crew and troops. First, a fully loaded forward countermeasure dispenser was impacted during the AH-1Z STA test series. Then, during the UH-1Y STA/NFUSL test series, both forward countermeasures dispensers were fully loaded and impacted.

Main Rotor Controls

Testing was done to determine continued operation following ballistic impact to the main rotor actuator, main rotor pitch link, and swashplate assembly. The main rotor actuator was set up in a fixture and shot to evaluate its potential to jam between the piston rod and cylinder walls. The pitch link was tested under a static load and shot creating single and double aperture penetration, followed by post-damage fatigue testing. The swashplate assembly was also tested under static load conditions. Areas of impact included the rotating and non-rotating ring structure, rotating ring clevis, and actuator fitting. As was the case with the pitch link, the swashplate assembly was subjected to post-damage fatigue testing.

Summary

The LFT&E program for the H-1 Upgrade aircraft was extensive and effective, with 21 ballistic test series completed, including FUSL testing, and nearly 300 shots. Many different critical flight systems were challenged to determine their ballistic response, which before testing were not fully known or understood. Ballistic testing also fulfilled the requirements of the LFT&E TEMP and provided valuable data with which to verify the effectiveness of ballistic vulnerability-reduction techniques incorporated in the aircraft.

A great deal has been learned from the LFT&E program. However, completion of the test program does not mean the job is over. Several survivability issues have emerged as result of ballistic testing. These issues will need to be addressed

and resolved so the aircraft continues to improve and survive in the battlefield. The H-1 Upgrades aircraft will continue to proudly serve the USMC just as its predecessors have done over the decades. However, with the overall improvements incorporated into the AH-1Z and UH-1Y, including those related to survivability, these aircraft will be even more effective and viable assets. ■



Mark Stewart

Excellence in Survivability

■ by Dale Atkinson

The Joint Aircraft Survivability Program Office (JASPO) is pleased to recognize Mr. Mark Stewart for Excellence in Survivability. Mark is a Principal Systems Engineer at Lockheed Martin in Fort Worth, TX, where he is the F-35 Technical Lead for Vulnerability Analysis and Live Fire Test. Mark graduated from the University of Florida in 1983 with a BS in Mechanical Engineering and went to work at General Dynamics after graduation. Over the years, General Dynamics became a part of Lockheed, which later became Lockheed Martin. His initial assignments included the development of an in-house surface-to-air missile (SAM) engagement model, F-16 Fast Shotline Generator (FASTGEN)/Computation of Vulnerable Area Tool (COVART) analyses, and F-16 analyses of both SAM and anti-aircraft artillery (AAA) threats.

In 1985, Mark was assigned to the Advanced Tactical Fighter (ATF) program, which eventually evolved into the F-22. He initially worked on external blast overpressure analysis and eventually developed a model that would generate sure-safe

and sure-kill regions around fast-moving aircraft platforms. During his approximately 12 years on the F-22 program, Mark was responsible for all ballistic vulnerability analyses. He also developed dozens of computer programs to serve as tools in the creation and manipulation of vulnerability target models, and in the reduction and visualization of the results from FASTGEN/COVART. Other models were developed to aid in the analysis of redundant air vehicle subsystems, providing insight for critical F-22 design decisions. During this time, Mark conducted F-22 live fire tests, provided test predictions for F-22 live fire tests, and analyzed test data for incorporation into the F-22 vulnerability analysis.

During the 1980s and 1990s, Mark also served on a variety of special projects, including F-16 and F-22 derivative designs. Work varied from FASTGEN/COVART to Enhanced Surface-To-Air-Missile Simulation (ESAMS) analyses. In 2000–2001, Mark developed new vulnerability target models and conducted analyses of the F-16 Block-50 and Block-60 variants. In doing so, he utilized Computer Aided Three



dimensional Interactive Application (CATIA)-based solid models to significantly improve the fidelity of the geometric models and subsequent vulnerability assessments.

In 1997, Mark was assigned to the Lockheed Martin Joint Strike Fighter (JSF) program. There he conducted vulnerability assessments of early design configurations and worked with design integrated product teams (IPT) to make critical design decisions and to harden the aircraft. He eventually became responsible for all aspects of vulnerability analysis and live fire testing on the program. The small team eventually grew to 10 people. This team developed a comprehensive live fire test program consisting of more than 50 different test series, ranging from coupons, components, and subsystems through both full-scale and full-up system-level (FUSL) test assets as noted in the F-35 LFT&E article in this issue. To date, approximately one-third of these tests have been completed, utilizing the expertise at the Aircraft Survivability Test Facility of the 46th Test Wing at Wright-Patterson Air Force Base (WPAFB), OH, as well as the Weapons Survivability Laboratory of the Naval Air Systems Command at China Lake, CA. Vulnerability assessments for the F-35 variants continue today, with approximately 16 separate full-up F-35 analyses completed. Over the years in the Concept Development (CD) and the System Design and Development (SDD) phases, vulnerability has affected design in countless design trade studies.



The F-35 Joint Strike Fighter (JSF) Lightning II, built by Lockheed Martin, takes off for its first flight on Joint Reserve Base Fort Worth, Texas during a test of the aircraft's initial capability.

Mark has been married to his childhood sweetheart, Susan, for 25 years. They have three daughters: Carolyn, 16; Hannah, 11; and Erin, 8. Most of his spare time is spent at the softball or soccer field, watching one of his daughters play. Mark also enjoys woodworking, photography, playing the piano, and supporting his church.

It is with great pleasure that the JASPO honors Mr. Mark Stewart for his Excellence in Survivability contributions to the F-35, the survivability discipline, and the warfighter. ■



6–9 November, 2007
Naval Postgraduate School
Monterey, CA

Symposium Overview:

Aircraft Survivability will explore the synergy of electronic and complementary survivability technology, and the analytical and test resources to support their development and evaluation.

Areas of Interest:

- Emerging technology, combat lessons learned, new threats, and requirements
- Current thinking of leaders in the field, new ideas and future direction
- Status of relevant programs, testing, and experiments
- Promising work in government, industry, and academic labs



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CH-53E Joint Live Fire Ballistic Testing

■ by Joseph Manchor

Recent experiences in Iraq and Afghanistan have emphasized that although we attempt to mitigate the potential for enemy encounters, the enemy will still succeed in impacting our aircraft with its weapons. Tactics and special hardware will only temporarily delay these inevitable encounters. Eventually, the enemy will either develop new tactics or acquire new weapons that will result in some successful attempts to down our aircraft. It is therefore important to understand the vulnerabilities of our aircraft so that vulnerability-reduction efforts may be implemented as needed to mitigate the success of these enemy encounters.

Over the past several years, an operational CH-53E aircraft has been undergoing an extensive series of ballistic tests. The aircraft was acquired in 2004 from the Aerospace Maintenance and Regeneration Center (AMARC) at Davis-Monthan Air Force Base (AFB). This high-time, but flyable, aircraft was acquired specifically for this testing through the assistance and support of the H-53 Heavy Lift Helicopter Program Office (PMA-261). The testing itself had been sponsored and funded under the joint live fire (JLF) program, with the objective of evaluating the vulnerabilities of this aircraft. Lessons learned from this testing can be applied to future vulnerability-reduction efforts for both the CH-53E and its successor, the CH-53K.

Testing commenced in 2004 with dynamic testing of the aircraft's main and tail rotor blades and tail rotor drive shaft systems (see Figure 1). For these tests, the aircraft was affixed to a special fixture that allowed the aircraft to be brought to ground hover conditions, yet would hold the aircraft



Figure 1. CH-53E rotor and drive shaft systems vulnerability testing (2004).

stationary. The fixture also provided dampening of vibrations to mitigate the potential for entering ground resonance conditions. A special gun aiming and firing system was also used to enable accurate ballistic impact of the aircraft's rotating components. With the aircraft in hover, eight ballistic impact tests were conducted to the aircraft's main and tail rotor blades and tail rotor drive shaft.

This same aircraft was again used in 2005 testing of the aircraft's fuel systems. Hovering the aircraft was not required for these particular tests. The main rotor blades were removed to preserve and protect them for future tests. The aircraft was placed on elevated stands to allow realistic ground-to-air shotlines (see Figure 2). Eighteen ballistic tests were conducted to the aircraft's fuel tanks and fuel lines while these components were charged with fuel and operated under normal in-flight fuel flow rates and pressure.

The main rotor blades were reinstalled, and the aircraft was repaired for follow-on dynamic tests in 2006. Hovering the aircraft was again required for these tests to represent realistic loading and flight conditions for the tested components. The helicopter hover fixture and aiming system was reutilized for these tests (see Figure 3). Ballistic impacts were



Figure 2. CH-53E fuel systems vulnerability testing (2005).



Figure 3. CH-53E tail rotor system vulnerability testing (2006).

conducted to the aircraft's main and tail rotor flight controls and tail rotor transmission systems.

In addition to evaluating vulnerabilities of the aircraft, these tests also provided opportunities to evaluate new vulnerability-reduction technologies. For example, Figure 4 is a post-impact photograph of a new self-healing plastic sleeve. Similar sleeves could potentially be retrofitted over existing aircraft fuel transfer lines. The unique self-healing properties of these plastics might enable the continued operation of the fuel

transfer lines after incurring ballistic damage. A bullet hole is seen in the sleeve-encased fuel transfer line of Figure 4. The outer self-healing plastic sleeve has healed after penetration, encasing leaked fuel within the sleeve while also allowing continued fuel flow through the fuel transfer line.

This 3-year test program is complete and has provided valuable data to the CH-53E, CH-53K, and virtually all other rotor aircraft. Vulnerability-reduction efforts have already commenced for the CH-53K based on the data and



Figure 4. Self-healing plastic fuel line sleeve.

lessons learned from this testing. These efforts should help this successor to the CH-53E be more resilient to its inevitable encounters with the enemy. ■



F-22 Live Fire Test and Evaluation (LFT&E) Program

■ by Hugh Griffis

The F-22 Raptor replaces and complements the F-15 Eagle air-superiority fighter. The F-22 (see Figure 1) combines stealth design with the supersonic, highly maneuverable, dual-engine, long-range requirements of an air-to-air fighter, and it will have an inherent air-to-ground capability, if needed. The F-22 provides a first-of-its-kind air dominance capability with improved capability over current United States Air Force (USAF) aircraft. The F-22 is designed to defeat the quantitative advantage and emerging qualitative equivalency of aircraft employed by air forces worldwide. The F-22 ensures a clear advantage over future generation fighters.

The F-22 has an improved lethality capability that ensures first-look/first-kill in all environments. It also has the maneuverability and acceleration needed to ensure superiority over any known or projected threat in a close-in fight. Enhanced survivability is obtained through a balanced combination of supersonic cruise (without afterburner), reduced signatures, defensive systems, maneuverability, and low vulnerability. The F-22 provides the pilot significantly improved beyond visual range (BVR) situational awareness using highly integrated offensive and defensive functions. The cockpit design exploits the capabilities of these advanced systems without overwhelming the pilot.

Live Fire Test and Evaluation Management

In the early 1990s, the program had numerous discussions about the live fire test and evaluation (LFT&E) legislation. [1] As result of these discussions, the F-22 program planned and implemented a robust LFT&E program. The F-22 LFT&E



Figure 1. F-22

program used a system engineering (SE)-based approach that integrated quantitative requirements definition; historical combat and other test data (e.g., joint live fire); modeling and simulations (M&S); vulnerability reduction design features; and a rigorous test approach, including basic material, component, subsystem, and subassembly testing. Vulnerability analysis, calibrated by robust testing, was the cornerstone to establishing the air vehicle vulnerability posture.

Discussions about the LFT&E legislation continued for many years. As a result of these discussions, Congress directed the

National Research Council (NRC) to study the proposed F-22 Alternative LFT&E Plan. The NRC conducted a thorough 6-month review of the F-22 proposal. Based on the NRC report, the Under Secretary of Defense (Acquisition and Technology) waived the F-22 full-up system-level (FUSL) testing on 21 August 1997. Although FUSL testing was not required, the F-22 Alternative LFT&E Plan required the implementation of a robust LFT&E program. This plan was incorporated into the F-22 Test and Evaluation Master Plan (TEMP).

Program Management

The F-22 Program Office at the Aeronautical Systems Center (ASC), Wright-Patterson Air Force Base (WPAFB), OH, manages a distributed team of contractors. Figure 2 shows contractor responsibilities by regions of the aircraft. In this program, each contractor was responsible for designing their hardware and conducting LFT&E on their hardware.

Boeing conducted early developmental testing to provide the design team with

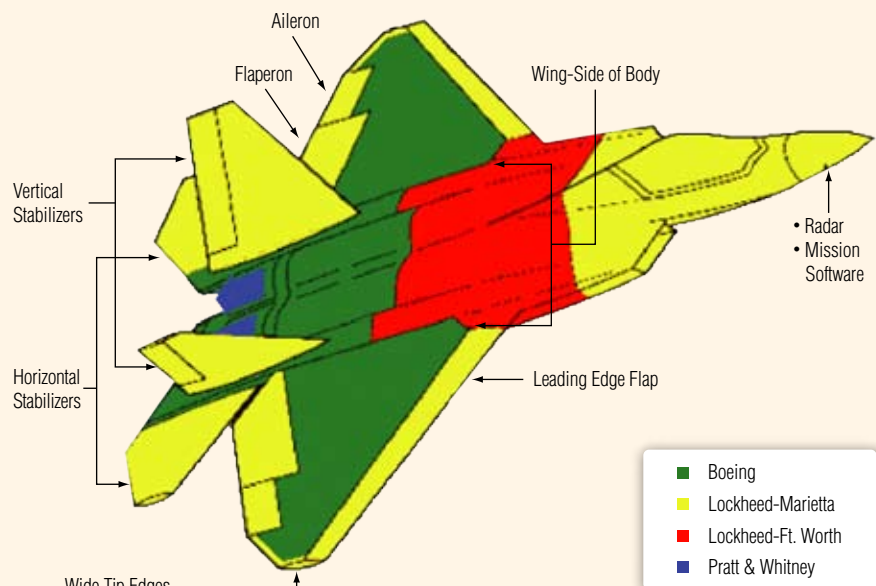


Figure 2. Contractor responsibility

insights relative to structural response to hydrodynamic ram loading. The majority of the F-22 ballistics tests were conducted at the 46th Test Wing Detachment at WPAFB, OH. The 46th Test Wing management, article design, and test expertise were used to implement a cost-effective and timely test program.

Vulnerability Analysis

A vulnerability analysis quantifies the vulnerability of aircraft. The measure of performance (MOP) of an aircraft's ballistic vulnerability is known as "vulnerable area." The F-22 team used the results of the vulnerability analyses to measure how well the aircraft design was performing in terms of meeting the design specification. Vulnerability analysis results define the vulnerability of sets of hardware. This information enables the design team to enhance the air vehicle vulnerability posture while imposing the least impact on the overall air vehicle. This information is used to optimize (*via* tradeoff in vulnerable area and weight) the air vehicle configuration.



Figure 3. Vulnerability Model

In a vulnerability analysis, thousands of shotlines are evaluated (about 650,000 single projectiles and about 70,000 burst points). During the entire F-22 LFT&E program, 20 individual test series comprising hundreds of tests were accomplished. In comparison to the number of shotlines evaluated during one simulation, it is clearly impractical to validate air vehicle vulnerability by testing alone. Detailed geometric models are used in modeling, simulation, and analysis to evaluate the air vehicle design. Figure 3 shows a vulnerability analysis three-dimensional geometric model of the F-22 structure and systems.

Although the F-22 program was using community standard analysis tools, it was

Table 1. Selection Criteria

Areas currently treated as invulnerable based on analysis both for which insufficient or contradicting data exists to support this assessment.
Compartments where the collateral damage mechanism cannot be assessed and that represent a potential vulnerability.
Components that represent a significant contribution to vulnerable area with insufficient data.
Basic material ballistic database is inadequate.

Table 1. Selection Criteria

clear that significant M&S improvements were needed. The F-22 and B-1 LFT&E programs initiated a new generation of improved vulnerability M&S tools, which the F/A-18E/F, F-35, C-5, C-130, Federal Aviation Administration (FAA), and many other systems have leveraged. The Joint Aircraft Survivability (JAS) Program is currently sponsoring Aeronautical Systems Center's Directorate of Engineering (ASC/EN) to grow the next spiral of vulnerability analysis MS&A tools.

Test Article Selection

Test articles were selected based on specific test criteria and vulnerability uncertainties. These criteria were chosen to reduce the uncertainties in the design features and modeling. Table 1 defines LFT&E target selection criteria.

Table 2. Modeling Uncertainties

Crew casualties caused by ballistic impact near the ejection system.
Structural failure induced by hydrodynamic ram.
Damage to critical components induced by high explosive blast.
Sufficient separation of flight-critical components to defeat the threat.
Damage to critical components induced by electromagnetic emissions.

Table 2. Modeling Uncertainties

Table 2 defines the F-22 vulnerability design and modeling uncertainties, which are based on F-22 vulnerability analyses.

Major Test Articles

Although various tests were conducted to support specific design and analysis issues, the bulk of LFT&E tests were related to four areas—

1. Fires within dry bays (a bay containing or adjacent to flammable materials)
2. Fires within engine nacelle
3. Hydrodynamic ram within fuel tanks

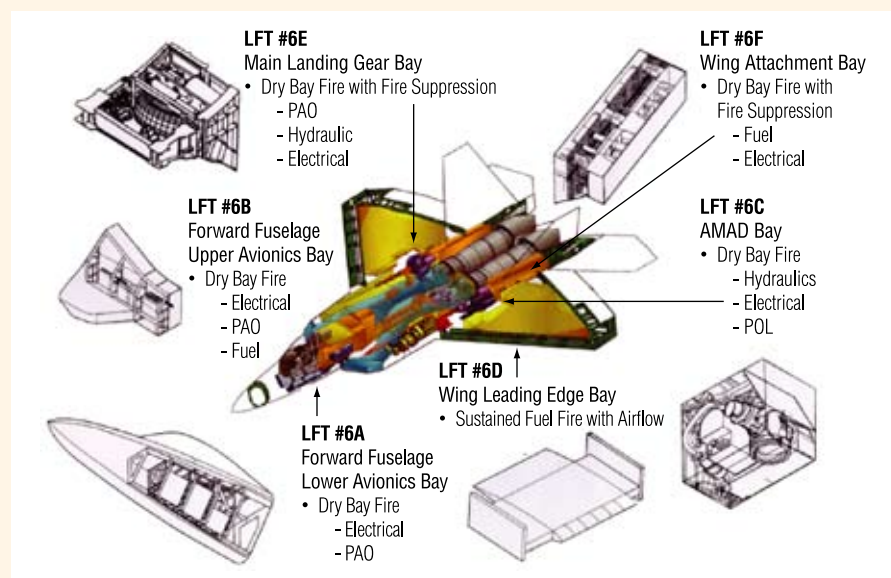


Figure 4. Dry bay vulnerability analyses.



Figure 5. Engine nacelle vulnerability analysis.

4. Ullage (the air space above the fuel) concentration within fuel tanks. Each of these areas is highlighted below.

More than 200 dry bay fire tests were completed to refine the system design and to calibrate vulnerability analyses depicted in Figure 4.

The engine nacelle and engine simulator, shown in Figure 5, are large test articles. Hundreds of safety fire tests were completed to refine the fire suppression system design. These tests were conducted under a wide range of environmental factors. After safety tests helped establish the design, ballistic tests were conducted to demonstrate the effectiveness of the fire suppression given ballistic threat-induced fires.

Figure 6 shows the first F-22 EMD aircraft being moved and set up for testing. This test demonstrates the wing's ability to withstand threat-induced hydrodynamic ram loading. Applying the correct flight loads on both wings and propagating those loads



Figure 7. Applying flight loads.

through the fuselage while providing the proper external air flow made this test complex. Figure 7 shows hydraulic actuators pushing up on whiffle trees to pre-stress the left wing structure.

Figure 8 shows the F-22 Fuel System Simulator (FSS) before the air vehicle top skin's installation. LFT&E used the FSS to demonstrate the air vehicle's ability to reduce oxygen content in the ullage for stressing mission flight profiles.

Summary

The F-22 program has planned and implemented a highly successful low-vulnerability and LFT&E program. The first LFT&E test was conducted in 1992. The last LFT&E-related test was completed in 2004. Tests conducted during the early portions of the development program supported the aircraft's design, and tests conducted late in the program demonstrated the aircraft's actual performance. All planned LFT&E tests and associated reports have been completed.



Figure 8. Ullage concentration

More than 20 individual test series were accomplished over the course of the F-22 LFT&E program. Each individual test series developed a test objective brief, test plan, and test report. Ballistic test results supported several design changes and more than 40 updates to the vulnerability analysis. These analysis updates incorporated new test data, changes in the aircraft design, and changes in analysis methodologies. These updated vulnerability analyses provided a more complete and accurate understanding of the vulnerability of the F-22.

These low-vulnerability and LFT&E activities have favorably altered the F-22 system design. These design changes enhance the combat survivability of pilots and the air vehicle. ■

References

1. United States Code (USC) Title 10, Armed Forces: Subtitle A—General Military Law; Part IV—Service, Supply, and Procurement; Chapter 139—Research and Development; Section 2366.



Figure 6. Moving F-22 into the 46th test wing range.



Lessons Learned from the Implementation of Live Fire Test and Evaluation (LFT&E) Program

■ by Hardy Tyson

It is difficult to separate vulnerability reduction from live fire test and evaluation (LFT&E), even though public law only requires a program to test, evaluate, and report. In part, this difficulty arises because the law requires that LFT&E “shall be carried out sufficiently early in the development phase...to allow any design deficiency demonstrated by the testing to be corrected in the design of the system... before proceeding beyond low-rate initial production.” Lessons can be drawn from observing the “success” of different approaches to LFT&E, wherein success is defined very narrowly as the ability to retain vulnerability reduction features in the aircraft through full-rate production of the aircraft. The observations in this article are drawn from the author’s participation in a number of aircraft acquisition programs that included LFT&E.

In all of the Navy/Marine Corps aircraft acquisition programs in which the author has participated, the aircraft specification has included requirements in terms of vulnerable area. A specification can state a required vulnerable area, or it can take the form of a probability of kill or probability of survival requirement.

Many of the requirements for aircraft programs state that a new design must be “as survivable as” or “no worse than” legacy aircraft. One should advocate moving away from this dependence on currently fielded aircraft and instead basing the requirement on more substantial operational community requirements, such as “no losses due to 23mm high explosives incendiary (HEI) threats.” As an alternative, the requirements could be derived from the Analysis of Alternatives. (In the past, the Cost and Operational Effectiveness Analysis [COEA] contained the requirements.) Campaign analyses often assume a low aircraft loss rate,

which allows for a sustainable conflict. This loss rate can be stated as a probability of kill at the aircraft level.

It is essential to conduct a vulnerability assessment as early as possible in the program. This assessment aids—

- the identification of the potential major contributors to vulnerability,
- discipline visibility, and
- management recognition.

It also evaluates the soundness, from a vulnerability perspective, of the basic design (*e.g.*, is the configuration such that fuel ingestion is impossible because there is no fuel in front of or adjacent to the inlet?).

There is an important point to be made here. Weight is a bane for all aircraft programs. As stated above, an aircraft design that has no fuel adjacent to the inlet does not require parasitic weight to prevent fuel ingestion, as would another design that has fuel adjacent to the inlet. The synergy that can exist with the need to protect against lightning strikes and ullage protection is another example of the weight burden. An On Board Inert Gas Generating System (OBIGGS) can weigh less than elements, such as grounding straps, that are required for a more traditional approach to lightning protection.

At this point, two different approaches can be taken within programs. Both approaches require a certain amount of knowledge about the discipline. This is where Dr. Robert E. Ball’s *The Fundamentals of Aircraft Combat Survivability Analysis and Design*

textbooks and the Survivability Short Course have played a huge role.

One approach is for a vulnerability advocate or champion within the company to identify vulnerability reduction features and work with each subsystem designer to incorporate these features to meet specifications. This can be a successful approach as long as the relationships between the advocate and the subsystem designers remain strong.

The other approach is to distribute among the subsystems a vulnerable area budget for each subsystem designer to work toward. This approach treats vulnerability reduction as a design process as opposed to a parasitic process, and it has had more success than the approach outlined above. This approach seems to necessitate a broader understanding of vulnerability reduction throughout the company and a bigger commitment by the company to educate its employees in the fundamentals of survivability (vulnerability reduction). It also appears to foster ownership of the vulnerability reduction features by the subsystems personnel as opposed to outsiders dictating how personnel should design their system.

The distribution of this budget is based on the vulnerability assessment. The budget can be redistributed among the subsystems to meet specifications as the design matures. A small amount of management reserve should be built into the budget to cover unknowns.

The first subsystems to be tested are usually those that are fixed early in the design. Structure fits into this category. The structure needs to allow for the redistribution of load around the damage

continued on page 31

F-35: First-Ever Fixed Wing Full-Up System Level

■ by Jeff Johnson and Timothy Staley

After 20 years of the live fire test law (10USC2366), nearly every type of aircraft has undergone testing, paving the way for programs to come. In spite of this long and impressive legacy of testing, the F-35 Joint Strike Fighter (JSF) program still marks many firsts.

The JSF's advances are partially a result of its lineage, which includes a multitude of disparate programs beginning in the mid-1980s, including the Advanced Short Take-Off/Vertical Landing (ASTOVL), Multi-Role Fighter (MRF), and the Advanced-Attack/Advanced/Fighter-Attack (A-X/A/F-X) programs. These eventually were rolled into the Joint Advanced Strike Technology (JAST) program. The resulting JSF program consists of three variants: a conventional takeoff (CTOL), short takeoff/vertical landing (STOVL), and carrier variant (CV). Although these variants share many components and design features, many variant-unique items require separate testing.

As the program prepared to exit the Concept Development Phase and enter the System Design and Development Phase, the JSF Program Office decided to pursue a waiver to the live fire test law. The office wrote and staffed an alternative live fire, which became the basis for



Early JAST concept from Boeing.

the waiver. The waiver limited full-up system-level (FUSL) testing to a single variant of the JSF and the Under Secretary of Defense for Acquisition, Technology and Logistics (OSD/AT&L) granted the waiver in June 2001. The waiver meant that though preceded by the F-22, the JSF will become the first fifth-generation fighter to undergo FUSL testing.

The Alternative Live Fire Test Plan was written before Milestone B and covered both the Boeing and Lockheed Martin designs. With the award of the System Design and Development (SDD) contract to Lockheed Martin, the alternative plan became the basis of the Lockheed Martin Master Test Plan. This new plan was documented in the first update to the Test and Evaluation Master Plan (TEMP), and the program began executing the plan almost immediately.

The focus of the live fire test and evaluation (LFT&E) program is to address the components or systems that have the greatest areas of uncertainty or the greatest amount of risk. This uncertainty includes unique aspects of the design and features that have little or no previous test data available. No aspect of the JSF is more unique than the STOVL propulsion system.

The STOVL propulsion system is a fascinating combination of very high performance parts. The system consists of a 22,000-pound thrust lift fan, driven through a very compact clutch by a shaft attached to the main engine fan. In the aft of the aircraft is a three bearing swivel module (3BSM), which rotates down 90 degrees for vertical flight. This module includes the engine nozzle, and the entire assembly is operated using fuelhydraulics. In fact, the STOVL X-35B is the first aircraft in aviation history to successfully use a shaft-driven lift fan propulsion system to lift a plane into the sky. As a result, these components warrant live fire testing. Thus far, the program has tested the ballistic tolerance of the 3BSM, the shaft, and the clutch, with the lift fan testing to come.



Early JAST concept from McDonnell Douglas.



F-35 AA-1 first flight.

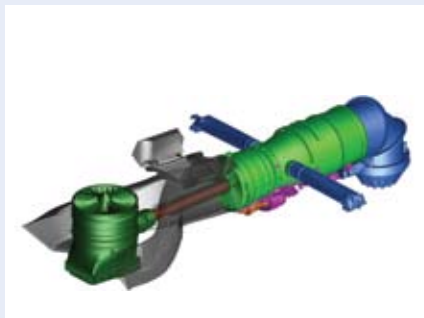


Figure 4. STOVL propulsion system.

An interesting design feature of all three variants is the bifurcated inlet duct, which has inlet openings on both sides of the fuselage, merging to a single inlet path just in front of the engine. The two inlets surround a large fuel tank on the CTOL and CV variants. As a result, any ballistic damage to this area can lead to leakage down the inlet and into the engine. The LF-12C test series conducted at China Lake tested the fuel ingestion tolerance of the JSF119-611 engine (Lockheed concept demonstration engine) using an inlet duct simulator. As the video of the tests shows, fuel ingestion can have very dramatic results. Because of the significant probability of a fuel ingestion event, and the fact that the JSF has only one engine, a liner for the forward fuselage tank between the inlets (F1 tank) was pursued. The program did several phases of testing on various liner approaches that could meet the performance needs of the engine while meeting the weight requirements of the airframe. In the end, the team developed a very effective design, but even that design was determined to be too heavy for aircraft and was removed. Further F1 tank testing using an F1 tank replica will



LF-12c fuel ingestion testing of F-135 Engine.

occur in the next year, with the intent of further quantifying leak rates and correlating predictions of hydrodynamic ram (HRAM) to actual shots.

As with nearly every other aircraft development program, the design of the JSF air vehicle system has been in a state of near-constant flux, with many changes occurring as the design matures. As these changes are made, the focus of testing has shifted. Tests once considered important have fallen by the wayside, and new tests addressing specific areas of uncertainty have been added to replace them.

One example of this shift in focus is the area of energetic materials. The original plan addressed ballistic damage to the flare dispenser. As the design began to solidify, the paucity of internal volume led to placement of the flare dispenser near the main fuel feed of the engine. This placement left no uncertainty regarding the outcome of an impact to the flare dispenser, and no reasonable way to protect the aircraft from such an impact. This testing was replaced with new testing of 23mm armor-piercing incendiary (API) rounds against graphite/epoxy composites and other materials used widely on all three variants of the JSF. In this case, there was very little data on the functioning characteristics of this API round against composites, leading to significant uncertainty in the analysis.

Another area that has been subject to considerable change is chemical and biological (C/B) warfare. Although many previous LFT&E programs did not address C/B threats, the hardness (ability to withstand the threats and continue to operate) of the JSF to C/B threats is covered in its Live Fire Test Plan. The original plan called for some limited material hardness and decontamination tests, culminating in a FUSL decontamination at the end of the LFT&E program. It became clear early on that this limited testing would result in significant risk of failure because of its occurrence so late in the program. The C/B team addressed risk areas by evaluating new C/B decontamination techniques on



Figure 6. Chemical/Biological decontamination risk reduction testing using an F-16.

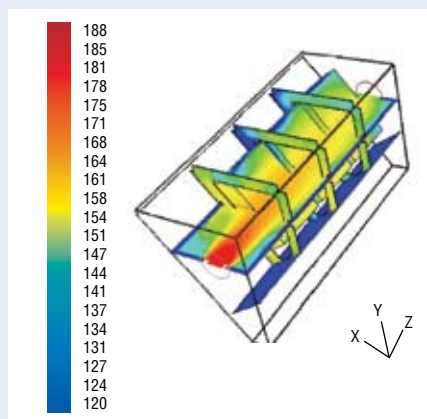
a surrogate F-16A aircraft. The C/B team conducted the testing at Edwards Air Force Base (AFB), demonstrating that a tactical aircraft could be successfully decontaminated without adverse effects.

Perhaps the most significant design change affecting the program's LFT&E relates to the fire suppression system. Several phases of testing were performed to determine the most lightweight and cost effective fire suppression system. The outcome of some of the testing, such as that performed by the 46th Test Wing at Wright-Patterson AFB (WPAFB), was quite spectacular. However, once again, weight constraints (among other factors) resulted in the removal of the fire suppression system (with the exception of fire detection) from the aircraft.

Although testing is the primary and most crucial aspect of LFT&E, the contribution of modeling and simulation (M&S) cannot be overlooked. Most of the testing mentioned above, including the F1 tank, C/B decontamination, and fire suppression system, relies to some degree on M&S.



LF-09c fire suppression system development testing.



Hot air decontamination temperature contour plot of "Chembox" using fluent.

Aside from the surrogate C/B testing, another part of the C/B decontamination risk mitigation is the detailed modeling of the airflow paths through the aircraft and heat transfer properties of the structure. This testing is being performed using the Fluent computational fluid dynamics model, and it should result in greater insight into airflow and decontaminant introduction locations and the time required to decontaminate the aircraft to the necessary levels.

On the ballistic side, hydrodynamic ram (HRAM) can significantly contribute to loss of aircraft with integral tanks, such as the JSF. As a result, a large amount of work has

been done on HRAM M&S and mitigation techniques. On the JSF, Lockheed Martin has used a tool called ARAM (Advanced Ram Assessment Method) to determine the extent of damage from an HRAM event. An initial use of ARAM for JSF was for pre-test predictions for a new HRAM mitigation technology. The prediction for the unprotected wing was favorable, but it was unfavorable for the protected wing. The unfavorable rating results at least in part from the fact that a good material model for the ram mitigation material did not exist. Ultimately, the results of the tests proved this mitigation technique ineffective. The pending F1 fuel tank testing mentioned above will be used for validation of ARAM for kinetic energy (KE) threats. If the results of this testing and analysis are favorable, ARAM will be used to supplement testing, allowing an assessment of HRAM damage for the JSF variants that will not be tested directly.

Even more so than HRAM damage, sustained fire is a tremendous threat to aircraft survivability. Furthermore, it is a very complex phenomenon and is not well understood, leading to a large amount of uncertainty regarding the overall vulnerability of the system. The program has attempted to make use of the Fire

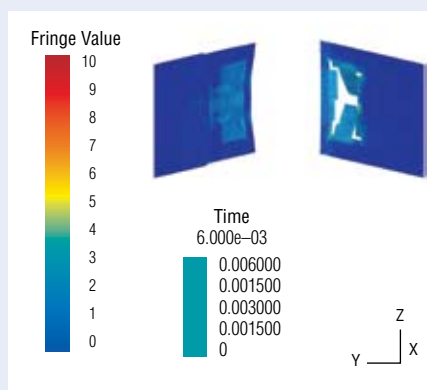


LF-11c roll post bay fire testing.

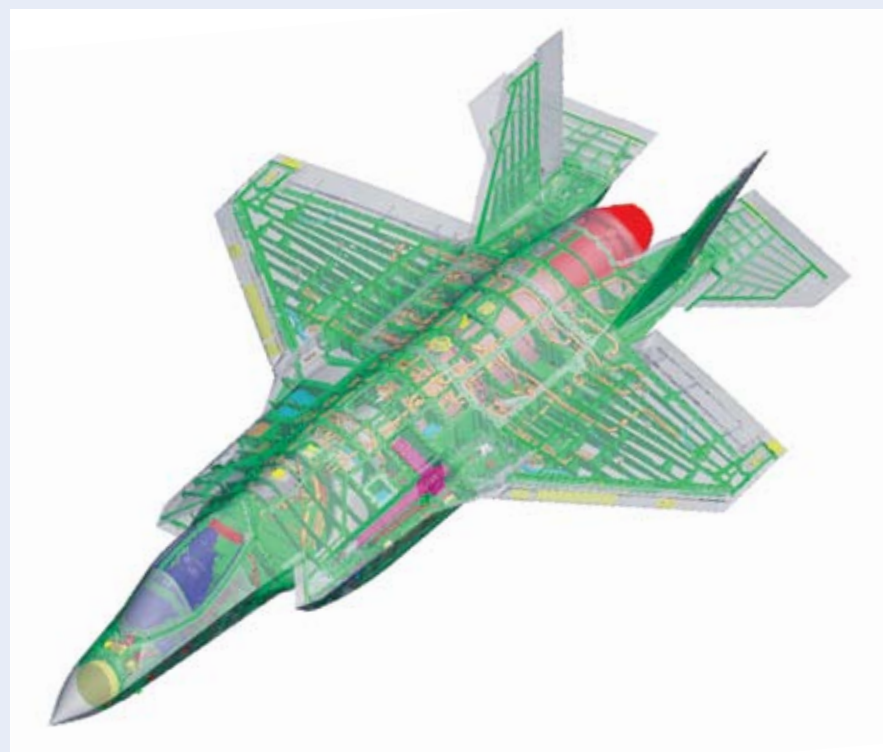
Prediction Model (FPM) for both pre-test prediction and test planning, as well as generation of probability of kill tables for use with Computation of Vulnerable Area Tool (COVART). Unfortunately, initial comparisons of FPM predictions with actual test data from JSF testing proved less than favorable. As a result, Lockheed Martin ceased using FPM in this role and instead relied on test data for similar materials and dry bay configurations to create fire Pk tables. Partly because of JSF's experience with FPM, the Joint Aircraft Survivability Program (JASP) funded the FPM Emergency Repairs project, examining the fundamental ground rules and assumptions of FPM, as well as comparing with test data from JSF, C-5, and other programs to determine the current state and path forward with respect to FPM. Lockheed



LF-03 HRAM mitigation testing using an F-16.



ARAM damage predictions for LF-02 HRAM testing.



FASTGEN target model of F-35A.



MANPADS aft boom testing on APOC test article.

Martin is currently reviewing the results of this study and will decide if FPM is suitable for use as originally intended.

In addition to its role in test planning and pre-test predictions, M&S is being used for specification compliance for the JSF program using Fast Shotline Generator (FASTGEN) and COVART. Lockheed Martin is generating the FASTGEN model using the CAD data also used to fabricate aircraft parts. Although this process results in a very detailed model and eliminates the need to build the model by hand, it does have its own unique set of issues. The most significant issue is the interpretation of this level of detail by FASTGEN and COVART—the fundamental methodologies of which were never intended for geometry as

infinitesimally small and detailed as the tessellated geometry that generally comes from CAD.

The JSF is being assessed against a wide range of threats, from API and high-explosive incendiary (HEI) rounds to fragments from proximity-fuzed surface-to-air missiles (SAM) and man-portable air defense systems (MANPADS). The MANPADS analysis uses the new advanced diverging ray methodology (ADRAM) and a localized area is being assessed, taking into account the areas of the aircraft where an infrared (IR)-guided MANPAD is more likely to impact. This analysis allows for more reasonable trade studies with respect to these threats, and ensures the program gets the most “bang for the buck” with any vulnerability reduction features implemented in the design.

In conclusion, although many aspects of the JSF LFT&E program set it apart from other programs (such as a STOVL lift system), many areas are recurring themes on all programs. These include the primacy of weight, cost, and schedule; changes in design throughout the program; and the political aspect of the live fire test

law. In the end, a successful live fire test program is one that can cope with an ever-changing program and manage all of the inevitable obstacles. ■

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“Lessons Learned From the Implementation of Live Fire Test Programs”

the spec threat could cause. Unless the designers have this information before completing their design, chances are low that the structure will successfully withstand this damage. This testing has the most value to the designer early in the program and has been accomplished during the Technology Development Phase of acquisition.

Live fire testing continues throughout the System Development and Demonstration Phase of the program at the component level. The critical components that have been identified during failure analysis or vulnerability analysis whose reaction to the threat is unknown are tested in this phase.

LFT&E can be used to verify the performance of vulnerability reduction features, such as an ullage explosion protection system or a dry bay fire protection system. This verification can be accomplished during the System Development and Demonstration Phase of the acquisition program.

Live fire testing culminates in full-up, system-level tests of full-up aircraft, usually during the Production Development Phase, so that the final LFT&E report can be sent to Congress before the full-rate production decision. This testing captures synergistic and cascading effects that might have been missed during component testing.

It would be impossible to conduct a live fire test program such as the one described here without contractor involvement. The services find themselves with added

challenges in implementing a live fire test program with performance-based specs because they cannot dictate the approaches the contractor should take.

Dr. Ball has taught us that aircraft survivability is a design discipline; we need to remember to treat it as one. ■

Calendar of Events

NOV

6–9, Monterey, CA
Aircraft Survivability
Conference 2007
<http://www.ndia.org>

27–30, Huntsville, AL
Modeling and
Simulation in
Electro-Optical and
Infrared Systems
<http://www.pe.gatech.edu>

26–28, Huntsville, AL
Helicon

DEC

3–7, Dayton, OH
Aircraft Fire
Protection/Mishap
Investigation Course
<http://www.Afp1fire.com>

4–7, Atlanta, GA
Infrared
Countermeasures
<http://www.pe.gatech.edu>

4–6, Nellis AFB, NV
JASP Model
Users Meeting

JAN

7–10, Reno, NV
46th AIAA Aerospace
Sciences Meeting
and Expo
<http://www.aiaa.org>

**23–25,
San Francisco, CA**
AHS Specialists’
Conference on
Aeromechanics

FEB

11–14, Monterey, CA
Warheads and Ballistics
<http://www.aiaa.org>

**25–28,
Palm Springs, CA**
24th Annual National
Test & Evaluation
Conference
<http://www.ndia.org>

27–29, Washington, DC
AUVSI’s Unmanned
Systems Program
Review 2008
<http://www.auvsi.org>

MAR

18–20, Washington, DC
Sea-Air-Space
[http://www.navyleague.org/
meeting_events](http://www.navyleague.org/meeting_events)

**23–27,
Warner Robins, GA**
Dixie Crow Symposium
<http://www.crows.org>

APR

7–10, Schaumburg, IL
49th AIAA/ASME/
ASCE/AHS/ASC
Structures, Structural
Dynamics, and Materials
Conference
<http://www.aiaa.org>

14–17, Monterey, CA
JASP Aircraft
Survivability Short
Course

**29 Apr–1 May,
Laurel, MD**
MSS ICRM Symposium
www.sensiac.gatech.edu

Information for inclusion in the
Calendar of Events may be sent to:

SURVIAC, Washington Satellite Office
Attn: Christina McNemar
13200 Woodland Park Road, Suite 6047
Herndon, VA 20171

Phone:
Fax:

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